Hydrostratigraphic and permeability profiling for groundwater remediation projects

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ABSTRACT: The success of in-situ groundwater remedies depends on a detailed understanding of the permeability structure of the contaminated aquifer because all systems are heterogeneous and anisotropic. A key requirement is to distinguish the permeable sand and/or gravel facies, where groundwater and contaminants move by advection, from the lower permeability silt- and/or clay-rich facies, where solute mass is stored and transport is dominated by diffusion. High-resolution stratigraphic data can be collected using cone penetrometer testing (CPT), direct push injection logging (DPIL) and direct push permeameter (DPP) methods. Conventional CPT soil behavior types group soils based on similar geotechnical mechanical properties, rather than the site-specific facies that capture meaningful aquifer permeability structures. The site depositional setting provides the framework to evaluate the facies trends between soundings using geological interpretations. The resulting high-resolution stratigraphic data can be analyzed with methods successfully used in the petroleum industry, enabling characterization of facies trends/depositional forms (in simpler systems) or classification of the depositional regime (in more complex systems). Through a process of site-specific calibration, these tools can be used to develop hydrostratigraphic interpretations that can be correlated to relative permeability. Concepts are illustrated through case studies where combinations of these techniques were utilized, highlighting advantages and disadvantages of each tool. These techniques are utilized to design and implement successful groundwater remediation solutions. An investigation strategy is advocated consisting of calibrated CPT to map general facies trends, and focused DPIL and DPP in areas where more detailed permeability measurements are required for the higher-permeability facies.

1 INTRODUCTION

High-resolution stratigraphy mapping techniques are essential for success in groundwater remediation projects, as local-scale variability of the permeability structure can have a controlling influence on groundwater flow, transport, and reagent distribution. In contrast with water supply projects, where definition of the average hydraulic properties of each hydrostratigraphic unit is sufficient, remediation projects require stratigraphic mapping methods that enable assessment of permeability trends that can be correlated with lithologic trends. High-resolution stratigraphic profiling is critical because even apparently homogeneous sand aquifers such as the Borden in Ontario show many orders of magnitude variability in permeability within a few meters thickness (Julian et al. 2001). Because advective flow and transport is concentrated in the highest permeability sand and gravel facies in an aquifer, which is referred to as the mobile porosity, long-term pumping tests tend to average-out the detail resulting in dramatic under-predictions of transport velocities in many cases. In addition, diffusive contaminant mass exchange to and from the less permeable silt and clay facies, which is referred to as the immobile porosity because transport is dominated by diffusion, results in much slower velocity in these aquifer segments than average hydraulics would predict (Payne et al., 2008). The resulting transport behavior leads to "rebound" following treatment via fast-acting methods such as in-situ chemical oxidation, or pump and treat remedies that continue decades after conventional approaches would predict site cleanup.

The goal is to map the stratigraphy at sufficient vertical resolution to show facies trends such as fining upward sequences, channels, and interbedded zones to facilitate geologically-based interpretation at and between soundings, while allowing site-specific calibration of relative permeability measurements against point permeability estimates in a manner similar to Liu et al. (2009). Fortunately, CPT and direct push injection logging (DPIL) techniques provide a near-continuous stratigraphy profiling that can be readily calibrated using pore-pressure dissipation and point permeability testing methods for the low- and high-end of the permeability spectrum, respectively. In this paper, these methods of stratigraphic profiling are evaluated and compared with an emphasis on using the data to evaluate facies trends and permeability structure in aquifers. An alternative approach to CPT data interpretation is presented that uses the shape and magnitude of response of the tip, sleeve, and pore-pressure sensors to interpret the data, much like in geophysical logging. This approach de-emphasizes the literal interpretation of soil behavior type and focuses on relative permeability profile and facies correlations that can be made more quantitative using site-specific calibration. The discussion is presented in the following sections using case studies to illustrate the concepts.

2 CASE STUDIES

2.1 *Case Study 1 – Quantitative Stratigraphic Profiling*

The goal of this case study was to create a high-resolution map of the hydrostratigraphy and contaminant distribution to explain complex plume behavior and select an appropriate remedy. The site is located in a coastal depositional setting with a shallow surficial aquifer composed of a sequence of beach ridge and dunes (clean sands) transitioning to shallow marine terraces (interbedded silts, clays, and sands) and a marine clay at the base. The site hydrostratigraphy consists of an Upper Sand (fine to very fine sand); an Interbedded Zone, which consists of thin beds of silt, clay, and fine sands that are sometimes dissected by fine to medium sand channels; the Lower Sand (fine to medium sands with coarse to very coarse shell hash); and the underlying regional confining unit (marine clay). A combination of CPT, electrical conductivity (EC), direct push injection logging (DPIL) and pneumatic slug tests (PSTs) were used to develop a quantitative hydrostratigraphy model.

Figure 1 shows the typical hydrostratigraphic profile obtained at the site and compares the results obtained using CPT, EC, DPIL and PSTs during the site-specific calibration process that was used during the project. The two panels on the right of the figure illustrate the SBTs, CPT responses, and hydrostratigraphic unit (HSU) designations at the site. The three panels to the left show the normalized DPIL pressure (using a Geoprobe hydraulic profiling tool (HPT) injecting at nominally 500 milliliters per minute); EC logging obtained during membrane interface probe (MIPs) soundings, which was performed during the CPT; and a comparison of PST hydraulic conductivity estimates, which were collected during groundwater sampling using a direct push rig using a 1m (3-ft) retractable screen, with the DPIL-inferred hydraulic conductivity.

In developing the hydrostratigraphy model for the site, the results of the pore-pressure, tip, and sleeve sensors were used to interpret the facies trends by evaluating the shapes of the curves. The first step in the process was to use the pore-pressure response to identify relatively low permeability marker units for correlation: the dominant low permeability feature was the interbedded zone, which was shown by the serrated, elevated pore-pressures between 12.2 and 14.6 meters below ground surface (bgs); and the confining unit, which occurred at depths below 16.2 m bgs. The Upper Sand (0 to 12.2 m bgs) and Lower Sand (14.6 to 16.2 m bgs) were identified based on modest pore-pressures above the hydrostatic pressure trend. The shapes and magnitude of the CPT responses were used to evaluate facies trends (grain size and bed morphology) for correlation between the soundings. Calibration of the HSU facies interpretations was completed using PSTs and DPIL-inferred permeability estimates, as discussed below.

The DPIL normalized pressure mirrors the pore-pressure response from the CPT and provides a consistent facies interpretation, based on the shape and magnitudes of the response curves. DPIL results identify low permeability facies with pressures above three to five tons per square foot (TSF) (note: 1 TSF = 95.7605 kPa) and relatively permeable facies with pressures near two TSF (3rd panel from right, Figure 1). Note that slightly better resolution of the Upper Sand facies variability is obtained using DPIL in the top 6.1 m as a result of continuous water injection during advancement. The relative permeability profile can be inferred from the DPIL results using the instantaneous flow measurements divided by the normalized pressure response (subtracting hydrostatic pressure) after Butler et al. (2007) and Liu et al. (2009). The DPIL-inferred hydraulic conductivity correlated with PST estimates (5th panel from the right, Figure 1). However, as with the CPT pore-pressure response, the DPIL has a thresh-hold DPP limit of resolution that is determined by the injection flow rate and precision of the pressure transducer (based on results obtained from site-wide analysis not included in this paper). This DPP limit is shown by the "flat-line" response on the order of 10^{-2} cm/s (note 1 cm/s = 10^{-2} m/s) in Panel 5. This approach was used at several calibration soundings to develop a quantitative mapping between facies and permeability in a three-dimensional hydrostratigraphy model for the site.

The utility of the EC logging and CPT SBT classification for quantitative facies correlations was limited at this site. In the case of EC response, there was a reasonable correlation between the high-response in the interbedded zone and lower marine clay, but the resolution of depth intervals and relative magnitude of response did not show a consistent pattern that could be correlated with relative permeability. As shown in Panel 4 (Fig. 1), the EC response missed the lower conductivity lense at approximately 7.6 to 8.5 m bgs and averaged-out the interbedded nature of the shallow

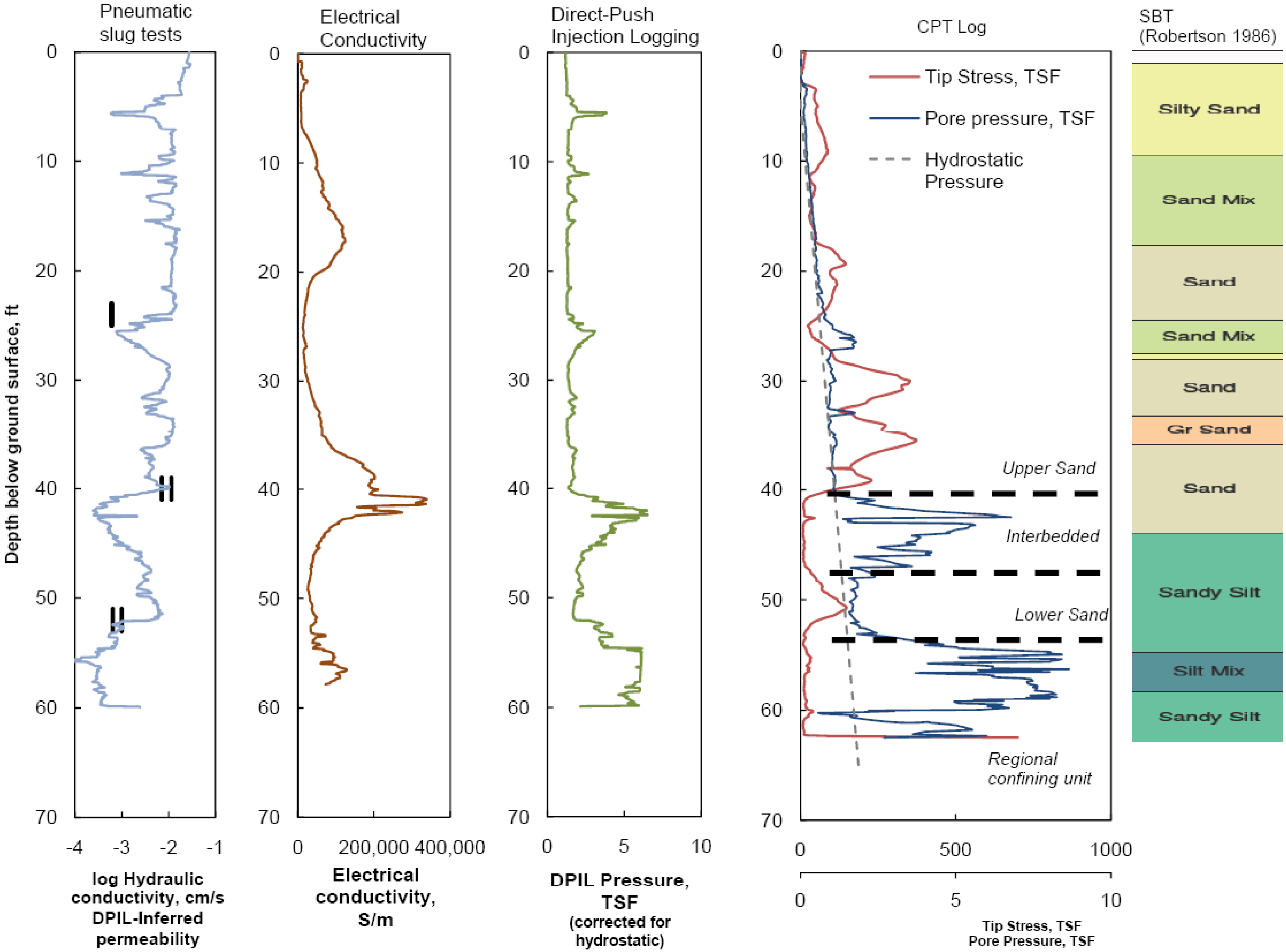

Figure 1. Case Study 1, showing pneumatic slug tests, electrical conductivity, DPIL pressure, CPT curves, and soil behavior types.

DPIL/CPT responses between 3.4 and 5.5 m bgs. In general, the SBT classification provided a better match to the relative permeability profile obtained from DPIL; however, the averaging associated with the graphical output often requires evaluating the pore-pressure to understand the bed morphology and facies trends, which was a key objective for this project. At other sites not considered here, site-specific calibration has led to very good correspondence between SBT and relative permeability profiles.

2.2 *Case Study 2 – Dissipation Testing and Permeability Profilingin Low-K Sediments*

The goal in this project was to refine a conceptual site model where potential DNAPL occurrence in fine-grained sediments would have a significant impact on remedy options. The site's depositional setting consists of a sequence beach ridge and dunes (clean sands) transitioning from the ground surface to shallow marine sediments (massive to interbedded silty clays) at the base of the CPT soundings. In this case, CPT was used for stratigraphic profiling as discussed above, but the focus was on profiling the permeability of the aquifer using pore-pressure dissipation tests (PPDT) to calibrate pore-pressure responses across the site in low permeability silts and clays. An additional goal was to determine the upper-limit of resolution for PPDTs to estimate hydraulic conductivity.

During the CPT profiling, PPDTs were recorded at 1 foot intervals at several calibration soundings in the early stages of the project. As the CPT was performed with a MIP, the "pause" required to stabilize the MIP equipment was used as an opportunity to perform fixed duration PPDTs, using the truncated recovery approach described by Parez and Farriel (1998). Figure 2 compares the CPT pore-pressure response (right panel) with the calculated hydraulic conductivity from 29 PDDTs over a 9.1 m interval. While there were a limited number of PDDTs that led to unusable data at other sounding locations due to long recovery times or poor data quality, the results at this location were consistently good. As shown in the plot, there is a strong correlation between the magnitude of excess pore-pressure above the hydrostatic line and decreasing permeability. Note that the PPDT results between 5.5 and 8.5 m, where CPT pore-pressures were negligible, the hydraulic conductivity was estimated at $>10^{-3}$ cm/s based on the signal-to-noise ratio for pressure transducers at very low excess pore-pressure. The range of permeability for the sands in this interval was estimated using the Kozeny-Carmen relationship (Payne et al., 2008) for grain-size analysis between 10^{-2} and 10^{-3} cm/s at other locations.

One of the key advantages of this approach is that after calibrating the pore-pressure response via PPDTs, it is possible to use the raw pore-pressure data in a more quantitative way to understand the relative permeability in profile. So, while the calibration process is time intensive, it's not necessary to perform the PDDTs at every MIP- or rod-break for the remainder of the investigation process.

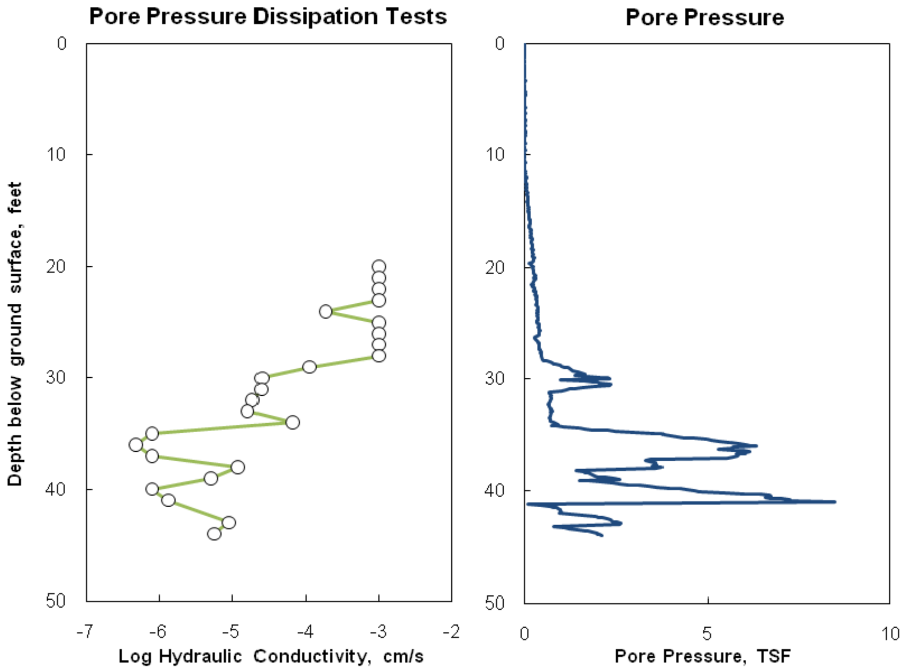

Figure 2. Case Study 2, showing pore pressure dissipation test results and CPT pore pressure. Note: 1 cm/s = 10^{-2} m/s; 1 TSF = 95.7605 kPa; 1 ft = 0.3048 m.

2.3 *Case Study 3 – DPIL Calibration Using DPP*

The goal in this project was to develop a refined conceptual site model and develop a remedy strategy. Based on prior soil sampling, it was expected that the stratigraphy for the site was a sequence of Aeolian dunes and associated fluvial deposits ranging from very fine to coarse sands and isolated silts. Prior hydraulic conductivity estimates obtained through mill-slotted, polyvinylchloride well screens ranged from 10^{-4} to 10^{-3} cm/s.

The stratigraphic profiling was conducted using CPT, DPIL, and direct push permeameter (DPP) and a deliberate calibration procedure. As expected based on the relatively high permeability of the aquifer, limited excess pore-pressure was observed in the CPT soundings as shown in the right panel of Figure 3. DPIL was completed using experimental HPCone developed by The In-Situ Group (Orlando, Florida), which consists of a CPT string modified to include an injection flow port with flow control and back-pressure transducer and three additional pressure transducers placed at 0.05 m, 0.15 m, and 0.40 m above the flow port. The CPT pore-pressure sensor is placed 0.40 m below the flow port. The equipment was operated in two modes – DPIL with a steady flow of 0.5 L/min (8.3 x 10^{-6} m^3/s) and DPP with the capability to inject at up to 3.0 L/min (5.0 x 10^{-5} m^3/s). During DPP mode, the operator would wait for pressure dissipation following DPIL and then run a sequence of DPP tests between 0.5 and 3 L/min, while logging the pressure response at the 3 DPP pressure transducers. Based on instrument calibration, it was expected that the instrument would resolve hydraulic conductivities up to 10^{-2} cm/s in DPIL mode and up to 5 x10^{-1} cm/s in DPP mode.

The DPIL and DPP data were analyzed using the methods described in Liu et al. (2009). The results are shown in the left panel of Figure 3. In this case, the DPIL results that are shown were normalized using the DPP data and a least-square regression approach. This approach translates the DPIL curve in hydraulic conductivity space to align the estimates better with the DPP results. As shown on Figure 3, the hydraulic conductivity ranges from the upper-limit of DPP resolution at 5 x 10^{-1} cm/s near the top of the sounding to 2 x 10^{-2} cm/s near the bottom. The DPE-calibrated DPIL conductivity profile shows permeability that extends beyond this level, in some cases by more than an order of magnitude, which raises questions about the need to truncate DPIL estimates in these intervals.

As for the PPDT calibration process described above, the goal is to calibrate the DPIL response using DPPs so that subsequent investigation efforts can be completed with less frequent DPE testing. In an attempt to provide better resolution of the high-permeability facies that were encountered in the example on Figure 3, the DPIL injection rate was increased to 2 to 3 L/min; however, modest permeability at these other soundings (not shown) resulted in issues with flow control and back-pressure transducer limits, as well as longer pore-pressure dissipation between each DPIL run. Due to these equipment limitations, more reliable and repeatable results were obtained using DPIL injection rates of approximately 0.5 L/min followed by DPP up to 3 L/min. While this approach limits resolution of the most permeable facies in the aquifer, the approach was successful in accurately resolving hydraulic conductivities almost two orders of magnitude higher than CPT or HPT alone.

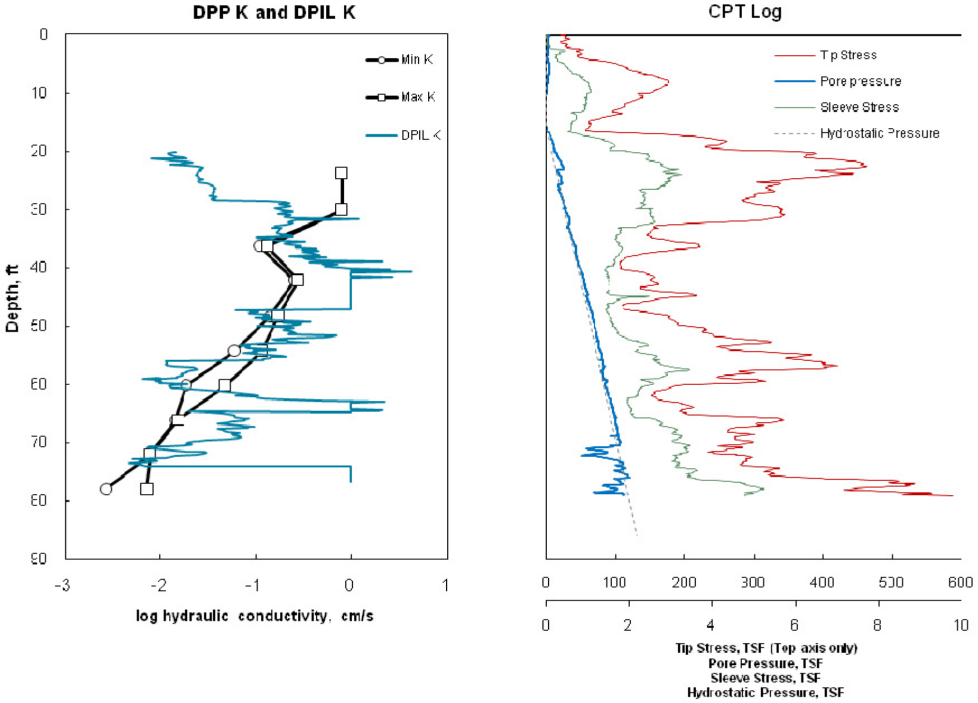

Figure 3. Case Study 3, showing DPP, DPIL and CPT results.
Note: 1 cm/s = 10^{-2} m/s; 1 TSF = 95.7605 kPa; 1 ft = 0.3048 m.

3 CONCLUSIONS

CPT methods can be extended to relative permeability mapping using the pore-pressure sensor response. Comparison with HPT and DPIL shows a consistent and accurate differentiation of low-K from high-K facies, which is one of the first steps in developing quantitative hydrostratigraphy models for groundwater remediation sites. A key advantage of the CPT tool is the capability to perform PPDTs at each rod-break, which provides accurate estimates of permeability up to approximately 10^{-3} cm/s. Site-specific calibration using PSTs or DPP enables resolution of higher conductivity values, which extends the facies correlation techniques advocated.

DPIL and DPP techniques provide a window into a higher range of conductivity in the coarser-grained facies, extending the resolution limit up to 10^{-2} and near 10^{0} cm/s. When used in combination for a site-specific calibration, it is possible to use the DPIL curve response to map the facies and correlate the curves to all but the highest absolute hydraulic conductivity values. While continued advancement in measurement techniques and instrumentation will undoubtedly extend the DPIL resolution in the future, for now the best approach is to test the limits at our sites and determine when PSTs are required to extend the range beyond 10^{-0} cm/s.

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